PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G11B 5/596

A1

(11) International Publication Number: WO 97/4583[illegible]

(43) International Publication Date: 4 December 1997 (04.12.97)

(21) International Application Number: PCT/US97/08638

(22) International Filing Date: 21 May 1997 (21.05.97)

(30) Priority Data:
08/655,916 31 May 1996 (31.05.96) US

(71) Applicant: SYQUEST TECHNOLOGY, INC. [US/US]; 47071 Bayside Parkway, Fremont, CA 94538 (US).

(72) Inventors: PHAM, Ich; 7087 Kindra Hill Drive, San Jose, CA 95120 (US). DROUIN, David; 1156 Tice Drive, Milpitas, CA 95035 (US). HOWARD, Evelyn; 204 Ellyridte Court, San Jose, CA 95123 (US).

(74) Agents: ROUSE, Thomas, R. et al.; Lyon & Lyon LLP, Suite 4700, 633 West Fifth Street, Los Angeles, CA 90071-2066 (US).

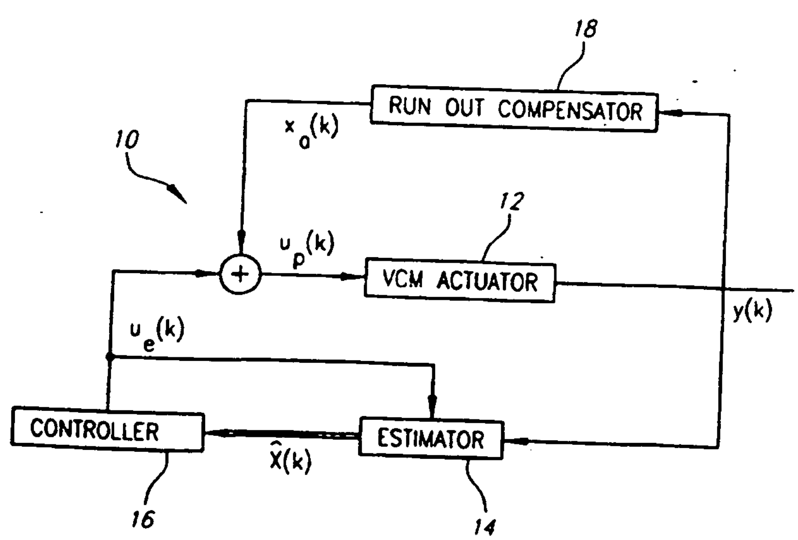
(81) Designated States: CA, CN, JP, KR, SG, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: METHOD FOR APPLYING OPTIMAL SEEKING TECHNIQUE TO DISK FILE WITH EXCESSIVE REPEATABLE RUNOUT

(57) Abstract

A method for applying an optimal seeking technique to a disk file with excessive repeatable runout includes a method of modifying a control signal ($u_e(k)$) provided by a controller (16) for controlling a rotary actuator arm (12) of a disk drive. The control signal ($u_e(k)$) is modified during track seeking by adding a runout state ($x_a(k)$) that is calculated each time a servo sector of a target data track on a surface of a disk is sampled by read/write heads carried by the actuator arm by a runout compensator (18). The modified control signal ($u_p(k)$) is provided to the actuator (12) for positioning the head to a desired track. A calibration algorithm can be used during track following to determine runout magnitude and runout phase at various preselected calibration tracks on the surface of the disk. A seeking algorithm can be implemented to compensate for the relative runout magnitude and phase variation between calibration and target tracks.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania
AM	Armenia
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

DESCRIPTION

METHOD FOR APPLYING OPTIMAL SEEKING TECHNIQUE TO DISK FILE WITH EXCESSIVE REPEATABLE RUNOUT

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Serial No. 08/615,076, filed March 13, 1996.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention pertains to the field of disk drives, and more particularly to a method for applying an adaptive seeking algorithm to a removable cartridge disk file with excessive repeatable runout.

Background

In a removable cartridge disk drive, the read/write heads, or transducers, of the drive must float directly above the centerline of any data track being accessed on the surface of the disk contained in the cartridge. Mechanical imperfections and geometric constraints cause the transducers to stray from track center, giving rise to a phenomenon known in the industry as repetitive runout. Repetitive runout occurs for several reasons, including repeatable bearing runout, imbalance between the rotating hub assembly and the disk, and disk clamping errors. Disk clamping errors, for example, are specific to removable media disk drives.

Imperfections such as the above create a variance between the center of the hub on which the disk sits and the center of rotation of the disk. This gives rise to a repeatable tracking error at the rotational frequency. Additionally, in a disk drive with a rotary actuator arm, the repeatable runout magnitude and phase vary with the position of the actuator arm. Further, repeatable runout can be time variant because the afore-

mentioned imbalances can change or the disk can slip during normal operation.

Conventional disk drives use digital servos with high bandwidths to compensate for repetitive run-out. This is effective for runout on the order of a fraction of a track. However, removable cartridge disk drives generally experience runout approaching several tracks. This is known as excessive repeatable runout. The conventional servo cannot compensate for excessive repeatable runout without sacrificing seeking performance.

A least mean square technique has been used to adjust tap weights for every servo sample based on the measured position signal. The method requires sine and cosine functions for tap weight adjustment and feed forward control signal calculation. Approximately one revolution of the disk is required for the tap weights to be adapted to the correct values for minimizing tracking error so that the drive can perform read/write operations. However, the runout adaptation time increases the settling time, causing access time to double. Moreover, the method alleviates track following error only; it ignores track seeking performance.

Another known technique is to use discrete Fourier transforms (DFTs) to identify the magnitude and phase of the repeatable runout. During calibration the microprocessor collects the position-error-signal data for several revolutions. The DFT calculation is then performed and the results are used to form the repeatable runout correction signal, which is stored for subsequent use during normal operations. The DFT procedure can be repeated continuously while the drive is track following and not engaged in read/write functions. The disadvantage of this technique is that it is slow, requiring several revolutions to derive the repeatable runout correction signal. The technique is also calculation intensive. A typical disk drive with sixty servo

sectors per revolution requires 120 multipliers and 119 adders to generate the DFT results from one revolution of the position-error-signal data. This mandates that an expensive microprocessor be used--an inadequate solution in the competitive disk drive industry.

Alternatively, a slower microprocessor could be used with the DFT calculation performed only at selected tracks; the DFT results would then be used to form the feed forward signal during normal operation. This technique would compensate for runout error dependent on the actuator position. However, the time-variant runout could not be addressed because the DFT would be based on prior runout information.

Another known method increases the typical disk drive state estimator from a third-order to a fifth-order model, which includes not only head position, head velocity, and bias torque, but also first and second runout states. The fifth-order state estimator can be used in either a hybrid runout compensator technique or a real time state space technique. In the hybrid technique, the fifth-order estimator is used during calibration to obtain runout correction values, which are stored in random access memory to be used in subsequent read/write operations. Because the fifth-order estimator is not used during normal operation, the dynamic can be selected to be relatively slow to avoid undue sensitivity of the estimator's performance due to the uncertainty in the measured position. The hybrid technique is less calculation-intensive than the DFT method, but it too is slow and unadaptive.

The real time state space technique is adaptive, but the fifth-order state estimator model is highly sensitive to noise. As the head moves across the track boundary during seeking, the error in the measured position can approach one-half of the track width--typically higher than the runout magnitude without correction. At least one-half of a revolution would have to

take place before the runout magnitude and phase could be compensated for.

Another disadvantage of a fifth-order estimator is that the model attempts to estimate the unknown runout and bias torque simultaneously, using only one input: the estimator error. This disadvantage can be overcome by choosing fast estimator poles for estimated position, velocity, and first and second runout states, but using a slower estimator pole for the estimated bias torque. However, such a design is inappropriate for the typical disk drive servo, which must perform well under a wide variety of conditions. For example, if the actuator bearing were to hit a small particle during arrival at the target track, the transient response--which is dominated by the bias estimator pole--would be too slow.

Another disadvantage of a fifth-order estimator model is that the extra calculation required (as compared to a conventional third-order model) generates more quantization error and reduces system throughput. This would be problematic in the disk drive industry because the typical low-cost disk drive uses only one microprocessor to process both servo and interface controller codes.

Based on the foregoing, there is a need for a method of calibration and seeking that (1) modifies the control signal during seeking, (2) determines the runout magnitude and phase at various tracks, and (3) compensates for the relative magnitude and phase variations between the originated and target tracks.

SUMMARY OF THE INVENTION

The present invention is directed to a calibration and seeking method that (1) modifies the control signal during seeking, (2) determines the runout magnitude and phase at various tracks, and (3) compensates for the relative magnitude and phase variations between the originated and target tracks. To these ends, a

method for applying an optimal seeking technique to a disk file with excessive repeatable runout during servo seeking of a target data track by a read/write head of a disk drive includes the steps of continually calculating a runout state of the target data track and using the calculated runout state to modify a servo control signal to compensate for runout error.

In a separate aspect of the invention, runout magnitude and runout phase are determined at various preselected data tracks. Advantageously, runout magnitude and runout phase are then determined at the target data track by interpolation. Preferably, compensation can be made for relative variation between the runout magnitude and phase at preselected tracks and the runout magnitude and phase at the target track. Other features, aspects, and advantages of the present invention will become better understood with reference to the following description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a simplified block diagram of a servo seeking system.

Fig. 2 is a partial plan view of a rotary actuator arm of a disk drive.

Fig. 3 is a block diagram of a continuous state estimator model.

Fig. 4 is a block diagram of the continuous state estimator model of Fig. 3 using a controller that is fed back into the estimator model.

Fig. 5 is a flow chart of a calibration algorithm for determining runout magnitude.

Fig. 6 is a flow chart of a calibration algorithm for determining runout phase.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning in detail to the drawings, Fig. 1 illustrates a simplified block diagram of a servo seek-

ing system 10 within a disk drive for a disk file with repeatable runout (RRO) that is constant across the surface of the disk. The voice-coil motor (VCM) actuator block 12 of Fig. 1 is known in the art. A power amplifier control signal $u_r(k)$ is fed into the VCM actuator block 12. A digital-to-analog converter circuit inside the VCM actuator block 12 converts the control signal $u_r(k)$ to an analog signal which is applied to a power amplifier inside the VCM actuator block 12 to generate a current to control the VCM. The VCM then generates a mechanical torque to rotate an actuator arm within the disk drive.

As shown in Fig. 2, which depicts a partial plan view of a disk drive 20, the actuator arm 22 carries a read/write head 24, or transducer, over a surface of the disk 26 to a concentric target data track 28 on the surface of the disk 26 to carry out read/write operations. With reference to Fig. 1, the VCM actuator block 10 generates a position output $y(k)$ specifying the position of the read/write head relative to the centerline of the target data track. The position $y(k)$ is a combination of a digital grey code track number and a fraction of the track provided by a position error signal (PES) of an analog-to-digital converter circuit (A/D) (not shown).

The estimator block 14 of Fig. 1 is a mathematical model of the VCM actuator block 12. It is known in the art to employ a third-order continuous (analog) state estimator model, such as the model shown in Fig. 3. In Fig. 3, K_a represents overall actuator gain. The actuator gain K_a includes the gain scale factor of the digital-to-analog converter circuit (D/A), the power amplifier gain, the VCM torque constant, the VCM inertia, and the radius distance from the rotary actuator arm pivot point to the read/write head. The "+" symbol

denotes summation of the input signals. The "$1/s$" symbol is a Laplace transform symbol denoting integration of the input signal.

The three variables comprising the state are defined as follows: $\hat{x}_1$ is the estimated position y_m; $\hat{x}_2$ is the estimated velocity; and $\hat{x}_3$ is the estimated bias torque, a constant, due to friction. The symbol u_e denotes the power amplifier control signal used in the estimator 14. Differentiating the state variables with respect to time yields the following continuous state estimator dynamic equations:

$$\frac{d\hat{x}_1}{dt} = \hat{x}_2$$
$$\frac{d\hat{x}_2}{dt} = K_s\hat{x}_3 + K_s' U_e$$
$$\frac{d\hat{x}_3}{dt} = 0$$

In vector form the three equations can be written as one:

$$\begin{vmatrix} \frac{d\hat{x}_1}{dt} \\ \frac{d\hat{x}_2}{dt} \\ \frac{d\hat{x}_3}{dt} \end{vmatrix} = \begin{vmatrix} 0 & 1 & 0 \\ 0 & 0 & K_s \\ 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} \hat{X}_1 \\ \hat{X}_2 \\ \hat{X}_3 \end{vmatrix} + \begin{vmatrix} 0 \\ K_s \\ 0 \end{vmatrix} U_e$$

Alternatively, $\dot{X}_e = F_e X_e + G_e u_e$,

and $y_e = H_e X_e$, where $H_e = |1\ 0\ 0|$. (1)

It is also known in the art to convert the continuous state estimator model of Fig. 3 to a discrete (digital) state estimator model for microprocessor implementation. Allowing for computation delay (which is defined as the time between the PES becoming available at the A/D input and the control signal becoming available at the D/A output), the discrete version of the model described by equation (1) is given by equation (2). Thus,

$$X_e(k+1) = \Phi_e X_e(k) + \Gamma_e U_e(k)$$
$$Y_e(k) = H_e X_e(k) \tag{2}$$

X_e, Φ_e, Γ_e, and H_e are matrices with dimensions 4x1, 4x4, 4x1, and 1x4, respectively. The calculation of Φ_e and Γ_e based on the continuous model given in equation (1) is known in the art. Equation (2) mathematically predicts the three states (position, velocity, and bias) of the next servo sample $k + 1$ for each servo sample k. The prediction is based on the estimated states and control signal of the present servo sample k. Equation (2) is modified by including a correction factor based on the measured position y, also denoted $\hat{x}_1$. The result, given

in equations (3) and (4), is an estimate of the states at servo sample $k + 1$ that is based on the sum of a mathematical prediction of the states at $k + 1$ and an error-correction component.

$$\bar{X}(k+1) = \varphi_e \hat{X}(k) + \Gamma_e U_e(k) \tag{3}$$

$$\hat{X}(k+1) = \bar{X}(k-1) - L(y(k-1) - H_e \bar{X}(k+1)) \tag{4}$$

$\bar{X}(k)$ is a 4x1 vector with components $\bar{x}_1(k)$, $\bar{x}_2(k)$, $\bar{x}_3(k)$, and $u_e(k-1)$.

Similarly, $\hat{X}(k)$ has components $\hat{x}_1(k)$, $\hat{x}_2(k)$, $\hat{x}_3(k)$, and $u_e(k-1)$. The error-correction component includes a design constant with dimensions 4x1, denoted L, which approximates estimator gain. The components of the vector L are l_1, l_2, l_3, and 0.

The controller block 16 of Fig. 1 is also known. A model for the controller block 16 is shown in Fig. 4. The model uses the estimated position, estimated velocity, and estimated bias to form the estimated

control signal u_e. The velocity trajectory $f(x)$, velocity feedback k_v, bias feedback k_b, and delay feedback k_d are selected according to conventional design methods. Thus,

$$u_e(k) = -k_v(f(\hat{x}_1(k)) - \hat{x}_2(k)) - k_b\hat{x}_3(k) - k_d u_e(k-1) \tag{5}$$

With reference once again to Fig. 1, the runout compensator block 18 can be used during track seeking in a preferred embodiment of the invention. During seeking, the runout compensator block 18 functions as a free-running oscillator at runout frequency ω. The

runout compensator block 18 is described by the following equations:

$$x_4(k+1) = x_5(k) \tag{6}$$

$$x_5(k+1) = -x_4(k) + \alpha x_5(k) \tag{7}$$

α is a design constant that is a function of the runout frequency ω and the servo sampling time T. Namely,

$$\alpha = 2\cos(\omega T) \tag{8}$$

The runout compensator block 18 of Fig. 1 generates an output signal $x_4(k)$ based on the runout state equations (6) and (7). The signal $x_4(k)$ is added to the control signal $u_e(k)$, as shown in Fig. 1, to compensate for runout in the position signal $y(k)$. Thus, $u_r(k) = u_e(k)$

$$+\ x_3(k) \tag{9}$$

The values of $x_3(k)$ and $x_4(k)$ must be initialized at the start of each seek to ensure that the $x_3(k)$ generated by the runout compensator block 18 will have the requisite magnitude and phase values to compensate for runout. The initialization is accomplished by using the measured position $y(k)$ as the input to the runout equations, as shown in Fig. 1, during track following. This procedure yields the following equations:

$$x_3(k+1)=x_4(k)-k_{31}y(k) \tag{10}$$

$$x_4(k+1)=x_3(k)+\alpha x_4(k)-(\alpha k_{31}+k_{41})y(k) \tag{11}$$

Selection of the poles k_{31} and k_{41} for both continuous and discrete implementation is known in the art. Thus, letting

$$m_4=\alpha k_{31}-k_{41} \tag{12}$$

yields the following equation:

$$x_4(k+1)=-x_3(k)+\alpha x_4(k)-m_4 y(k) \tag{13}$$

During track following, equations (10) and (13) operate in closed-loop fashion. As discussed above, $y(k)$ is used to generate $x_3(k)$, which is fed into the power amplifier of the VCM actuator block 12 of Fig. 1. This forces the VCM to track unknown runout. During track seeking, equations (6) and (7) operate with initial conditions set at the end of the prior track following. Thus, provided the runout is constant across the surface of the disk, $x_3(k)$ will always have the

requisite compensatory magnitude and phase values such that $y(k)$ will correspond to track centerline, or zero.

In operation, assuming constant RRO across the surface of the disk, the microprocessor performs the following steps. First, the microprocessor synchronizes with the hardware by obtaining the measured position $y(k)$. Second, the microprocessor forms the estimator error, which is the difference between the measured and estimated positions. Thus,

$$esterr(k) = y(k) - \bar{x}_1(k).$$

Third, the microprocessor corrects the estimated position, estimated velocity, and estimated bias, using the estimator error and the estimator gains l_1, l_2, and l_3. Thus,

$$\hat{x}_1(k) = \bar{x}_1(k) + l_1 esterr(k)$$
$$\hat{x}_2(k) = \bar{x}_2(k) + l_2 esterr(k)$$
$$\hat{x}_3(k) = \bar{x}_3(k) + l_3 esterr(k)$$

Fourth, as shown in Fig. 4, the microprocessor calculates the estimator control signal $u_e(k)$ based on the estimator position $\bar{x}_1(k)$, estimator

velocity $\bar{x}_2(k)$, estimator bias $\bar{x}_3(k)$, velocity feedback

gain k_v, bias feedback gain k_b, and control delay gain

k_d:

$$u_e(k) = -k_2(f(\hat{x}_1(k)) - \hat{x}_2(k)) - k_3\hat{x}_3(k) - k_d u_e(k-1)$$

Fifth, the microprocessor adds the estimator control signal $u_e(k)$ to the runout compensator signal $x_s(k)$ to obtain the power amplifier control signal $u_p(k)$. Sixth, the microprocessor sends $u_p(k)$ to a D/A converter circuit. Seventh, the microprocessor uses the mathematical estimator model (Φ_e, Γ_e), to estimate the position, velocity, and bias for the next servo sample. Eighth, the microprocessor determines whether it is in the track seeking or track following mode. It is in the track following mode when $y(k)$ is within one-half-track of the target track centerline. Otherwise, the microprocessor operates in the track seeking mode. In the track seeking mode, the following equations are executed:

$$x_s(k+1) = x_r(k)$$

$$x_r(k+1) = -x_s(k) + \alpha x_r(k)$$

In the track following mode, the following equations are executed instead:

$$x_s(k+1) = x_r(k) - k_{rs}y(k)$$

$$x_r(k+1) = -x_s(k) + \alpha x_r(k) - m_s y(k)$$

If the disk drive employs a single microprocessor for both servo and interface controller functions, the microprocessor can execute the interface code

while waiting for the next servo sample. On the other hand, if a dual-microprocessor design is utilized, the servo processor can either be idle, to save power, or perform housekeeping tasks while waiting for the next servo sample.

The above equations must be modified to compensate for RRO that varies with time or position on the surface of the disk. To this end a calibration is performed during track following at various idle times such as power up, cartridge insertion, and periodic moments when the disk drive is not engaged in read/write operations. In a preferred embodiment, the surface of the disk is divided into ten concentric zones. The servo therefore track follows at eleven preselected boundary tracks, using the runout state x_3 to determine the runout magnitude and the runout phase. Calibration at each preselected track takes approximately sixty-four milliseconds; thus, the entire calibration process takes about one second. In a preferred embodiment, the signal x_4 is a sinusoidal waveform with a frequency of sixty hertz, corresponding to 3600 disk revolutions per minute. During normal operation, the servo code at the beginning of a track seek interpolates between the runout magnitude and phase at present and target tracks to adjust x_3 and x_4 accordingly.

Figure 5 shows a flow chart for a calibration algorithm that determines the runout magnitude at each

preselected track *i*. The servo track follows at each preselected calibration track *i* and executes the previously described runout state calculations. Two peak values *j* of the runout state x_i are detected and averaged to determine the runout magnitude. The preferred servo system uses sixty servo sectors (sampling locations on a given data track) *n* per revolution of the disk. As shown in Fig. 5, one peak is obtained within each thirty servo sectors, so *n* is reset to zero each time it reaches thirty; otherwise, *n* corresponds to *k*, the number of samples. One revolution of the disk is required for calibration at each track *i*. The eleven runout magnitude values are stored for use during normal operations.

The function of each block depicted in the flow chart of Fig. 5 is discussed in greater detail for a preferred embodiment. In the block designated 30, the servo system prepares to perform a given servo sample *k*. In block 32 the servo maintains the read/write heads at one of the eleven preselected boundary tracks *i*. While the servo track follows, the previously described runout state calculations are executed. The servo then determines in block 34 whether magnitude calibration is in progress. If magnitude calibration is not in progress, the servo begins magnitude calibration by initializing the variables *n*, *j*, *peak*, and *rro_mag(i)* to zero as

shown in block 36. The variable *n* corresponds to the number of servo samples performed en route to obtaining a peak value, designated *peak*, of the runout state $x_d(k)$. As discussed above, thirty samples *n* are necessary to obtain the peak value, and two peak values are obtained so that an average can be taken. Thus, *j*, which records the number of peak values obtained, can have a value of zero, one, or two. The variable *rro_mag(i)* denotes the runout magnitude at preselected calibration track *i*.

In block 38 of Fig. 5, the absolute value of the runout state $x_d(k)$ is compared to *peak*. If the absolute value of the runout state $x_d(k)$ is not greater than *peak*, *n* is incremented by one as shown in block 42. Otherwise, *peak* is first set equal to the absolute value of the runout state $x_d(k)$ as shown in block 40. In block 44 the servo determines whether *n* is thirty. If *n* is thirty, one peak value has been obtained, and the servo reinitializes *n* and *peak* to zero, increments *j* by one, and increments *rro_mag(i)* by one-half of *peak* as shown in block 46. Then, or if *n* is less than thirty, the servo determines in block 48 whether *j* is two. If *j* is not yet two, then two peak values have not yet been obtained, so the servo increments *k* by one, as shown in block 52, and waits for the next servo sample *k*, as

shown in block 54. Otherwise (i.e., if j is two), the servo first sets a flag to indicate that runout magnitude calibration at track i has been completed, as shown in block 50, and then proceeds to the task of block 52.

Figure 6 shows a flow chart for a calibration algorithm that determines the runout phase at each preselected track i. During track following at each preselected calibration track i, the servo detects a servo sector number s, referenced from an index servo sector $s = 1$, at which the x_d signal has a magnitude of zero and a positive slope. This process is repeated during a second revolution to detect an additional crossover point. The runout phase is determined by averaging the two crossover points. Thus, the phase calibration requires two revolutions to complete. The number of samples k goes up to 120 in Fig. 6, while s, which otherwise corresponds to k, is reset to one each time s reaches sixty.

The function of each block depicted in the flow chart of Fig. 6 is discussed in greater detail for a preferred embodiment. In the block designated 56, the servo system prepares to perform a given servo sample k. In block 58 the servo maintains the read/write heads at one of the eleven preselected boundary tracks i. While the servo track follows, the previously described runout state calculations are executed. The servo then deter-

mines in block 60 whether phase calibration is in progress. If phase calibration is not in progress, the servo initiates phase calibration by setting the variables *n* and *rro_phase(i)* equal to zero as shown in block 62. The variable *j* corresponds to the number of servo sector points detected at which the runout signal $x_n(k)$ has a magnitude of zero and a positive slope. As discussed above, the detected servo sector point is referenced from an index servo sector number *s* (which is initially set to one), and sixty servo samples are required to detect the first of two such servo sector points, the average of which is used to perform the runout phase calibration. Thus, *j* can have a value of zero, one, or two. The variable *rro_phase(i)* denotes the runout phase at preselected calibration track *i*.

In block 64 of Fig. 6, the servo system determines whether the index *s* is sixty. If *s* is less than sixty, the servo increments *s* by one as shown in block 66. If, on the other hand, *s* is sixty, the servo initializes *s* to one as shown in block 68. Next, the servo determines in block 70 whether the runout signal for the present sample, $x_r(k)$, is greater than the runout signal for the prior sample, $x_n(k-1)$. If the answer is no, the servo determines whether *j* is two as shown in block 76. If instead the answer is yes, the servo de-

termines in block 72 whether the runout signal for the prior sample, $x_s(k-1)$, has a negative value. If $x_s(k-1)$ is positive or zero, the servo determines in block 76 whether j is two. If, however, $x_s(k-1)$ is negative, the servo increments j by one and increments *rro_phase(i)* by the value of s as shown in block 74. Then the servo asks if j is two as shown in block 76. At block 76, if j is not yet two, then two crossover servo sector points have not yet been detected, so the servo increments k by one, as shown in block 80, and waits for the next servo sample k, as shown in block 82. Otherwise (i.e., if j is two), the servo first sets *rro_phase(i)* equal to the nearest integer value of *rro_phase(i)* divided by two and sets a flag to indicate that runout phase calibration at track i has been completed, as shown in block 82, and then proceeds to the task of block 80.

In a preferred embodiment, the difference between the runout magnitude and phase at a given target data track and the runout magnitude and phase at the present track is determined at the beginning of the seek. The values of x_s and x_c are then initialized accordingly. For runout magnitude variation, the values of x_s and x_c used at the beginning of the seek are determined by linear interpolation. Thus, the x_s and x_c values from the previous track following sample are

multiplied by the ratio of the target and present runout magnitudes. For phase variation, the servo code freezes the x_a and x_b values for a number of servo samples that is proportional to the amount of the phase variation. For example, for a phase lead of about thirty degrees, the microprocessor freezes x_a and x_b for the first five samples of the seek, commencing execution of the previously discussed equations at sample number six. Similarly, for a thirty degree phase lag, the microprocessor inverses the x_a and x_b values and freezes them for twenty-five (thirty minus five) samples at the beginning of the seek.

In performing the above seeking algorithm, the microprocessor calculates the target runout magnitude and phase using the calibrated values as discussed. The microprocessor then determines the zone in which the target track, or cylinder, resides. The microprocessor then linearly interpolates between the calibrated values at the beginning and the end of the zone to obtain the target values for runout magnitude and phase. Thus, *target_mag = [(rro_mag(i + 1) - rro_mag(i))target_cyl]/N*, and *target_phase = [(rro_phase(i + 1) - rro_phase(i))target_cyl]/N*, where:

target_cyl denotes target track, or cylinder;

target_mag denotes runout magnitude at the target cylinder;

rro_mag(i + 1) denotes runout magnitude at the end of the zone;

rro_mag(i) denotes runout magnitude at the beginning of the zone;

N denotes number of tracks within a zone;

target_phase denotes runout phase at the target cylinder;

rro_phase(i + 1) denotes runout phase at the end of the zone; and

rro_phase(i) denotes runout phase at the beginning of the zone.

The microprocessor then adjusts x_d and x_p based on the runout magnitude variation. Thus,

$$x_d(k) = x_d(k)\,[target\_mag/present\_mag], \text{ and}$$

$$x_p(k) = x_p(k)\,[target\_mag/present\_mag].$$

The microprocessor also calculates the phase variation *phase_var* based on the present and target phases. Thus, *phase_var = target_phase - present_phase*, where *present_mag* and *present_phase* are the runout magnitude and phase at the present track, as determined at the beginning of the previous seek. When the next servo sample arrives, the microprocessor starts performing the eight steps previously discussed. However, the microprocessor begins executing the runout state equations only after a number of samples necessary to compensate

for the runout phase variation have taken place.

Thus, a method for applying an optimal seeking technique to a disk file with excessive repeatable runout is disclosed which (1) modifies the control signal during seeking, (2) determines the runout magnitude and phase at various tracks, and (3) compensates for the relative magnitude and phase variations between the originated and target tracks. While preferred embodiments have been shown and described, it will be apparent to one of ordinary skill in the art that numerous alterations may be made without departing from the spirit or scope of the invention. Therefore, the invention is not to be limited except in accordance with the following claims.

WHAT IS CLAIMED IS:

1. A method for compensating for excessive repeatable runout error during servo seeking of a target data track by a read/write head, the read/write head carried by a rotary actuator arm driven by a voice-coil motor of a disk drive, the target data track residing on a surface of a disk contained in a removable cartridge housed within the disk drive, the method comprising the steps of:

calculating a runout state of the target data track with each servo sample; and

modifying a control signal sent to the voice-coil motor with the target runout state to compensate for the runout error.

2. The method of claim 1, wherein said modifying step is accomplished by using a sinusoidal signal derived each servo sample from a measured position of the read/write heads relative to track centerline.

3. The method of claim 2, wherein the sinusoidal signal has a frequency of sixty hertz.

4. A method for compensating for excessive repeatable runout error during servo seeking of a target data track by a read/write head, the read/write head carried by a rotary actuator arm driven by a voice-coil motor of a disk drive, the target data track residing on

a surface of a disk contained in a removable cartridge housed within the disk drive, the method comprising the steps of:

estimating a position of the read/write heads relative to the center of the target data track, and to estimate velocity of the read/write heads and bias on the read/write heads;

obtaining a measured position of the read/write heads relative to the center of the target data track;

calculating an estimator error equal to the difference between the measured position and the estimated position;

correcting the estimated position and the estimated velocity and the estimated bias by using the estimator error and predetermined estimator gains;

deriving an estimator control signal;

deriving a sinusoidal signal from the measured position of the read/write heads relative to the center of the target data track;

adding the estimator control signal to the sinusoidal signal to create a power amplifier signal which compensates for runout; and

sending the power amplifier signal to the voice-coil motor to adjust the rotary actuator arm accordingly.

5. The method of claim 1, further comprising

the step of determining runout magnitude and runout phase at various preselected data tracks on the surface of the disk.

6. The method of claim 5, wherein said determining step is performed during track following.

7. The method of claim 5, wherein the number of preselected data tracks is eleven.

8. The method of claim 5, wherein said determining step comprises obtaining two peak absolute values of the sinusoidal signal, averaging the values, and adding the average to the measured runout magnitude.

9. The method of claim 5, wherein said determining step comprises detecting a first servo sector number at which the sinusoidal signal has zero amplitude and positive slope, detecting a second servo sector number at which the sinusoidal signal has zero amplitude and positive slope, and averaging the two detected servo sector numbers to determine the runout phase.

10. The method of claim 5, further comprising the steps of determining the runout magnitude at the target data track and compensating for the relative variation between the runout magnitude at various preselected data tracks and the runout magnitude at the tar-

get data track.

11. The method of claim 10, wherein said determining step comprises multiplying the sinusoidal signal by a ratio of the runout magnitude at the target track and the runout magnitude at a preselected track, the ratio involving values obtained during a previous target track seek, and wherein said compensating step is performed with linear interpolation.

12. The method of claim 5, further comprising the steps of determining the runout phase at the target data track and compensating for the relative variation between the runout phase at various preselected data tracks and the runout phase at the target data track.

13. The method of claim 12, wherein said determining step comprises freezing the sinusoidal signal for a number of servo samples that is proportional to the determined amount of phase variation, and wherein said compensating step is performed with linear interpolation.

14. A method for compensating for excessive repeatable runout error during servo seeking of a target data track by a read/write head, the read/write head carried by a rotary actuator arm driven by a voice-coil motor of a disk drive, the target data track residing on

a surface of a disk contained in a removable cartridge housed within the disk drive, the method comprising the steps of:

estimating a position of the read/write heads relative to the center of the target data track, and to estimate velocity of the read/write heads and bias on the read/write heads;

obtaining a measured position of the read/write heads relative to the center of the target data track;

calculating an estimator error equal to the difference between the measured position and the estimated position;

correcting the estimated position and the estimated velocity and the estimated bias by using the estimator error and predetermined estimator gains;

deriving an estimator control signal;

deriving a sinusoidal signal from the measured position of the read/write heads relative to the center of the target data track;

adding the estimator control signal to the sinusoidal signal to create a power amplifier signal which compensates for runout;

sending the power amplifier signal to the voice-coil motor to adjust the rotary actuator arm accordingly;

determining runout magnitude and runout phase at various preselected data tracks on the surface

of the disk;

determining the runout magnitude at the target data track;

compensating for the relative variation between the runout magnitude at the preselected data tracks and the runout magnitude at the target data track;

determining the runout phase at the target data track; and

compensating for the relative variation between the runout phase at the preselected data tracks and the runout phase at the target data track.

15. A method of compensating for excessive repeatable runout error during servo seeking of a target track by a read/write head, the read/write head carried by a rotary actuator arm driven by a voice-coil motor of a disk drive, the target data track residing on a surface of a disk contained in a cartridge housed within the disk drive, said method comprising the steps of:

calculating a runout state of the target data track with each servo sample; and

modifying a control signal sent to the voice-coil motor with the target runout state to compensate for the runout error.

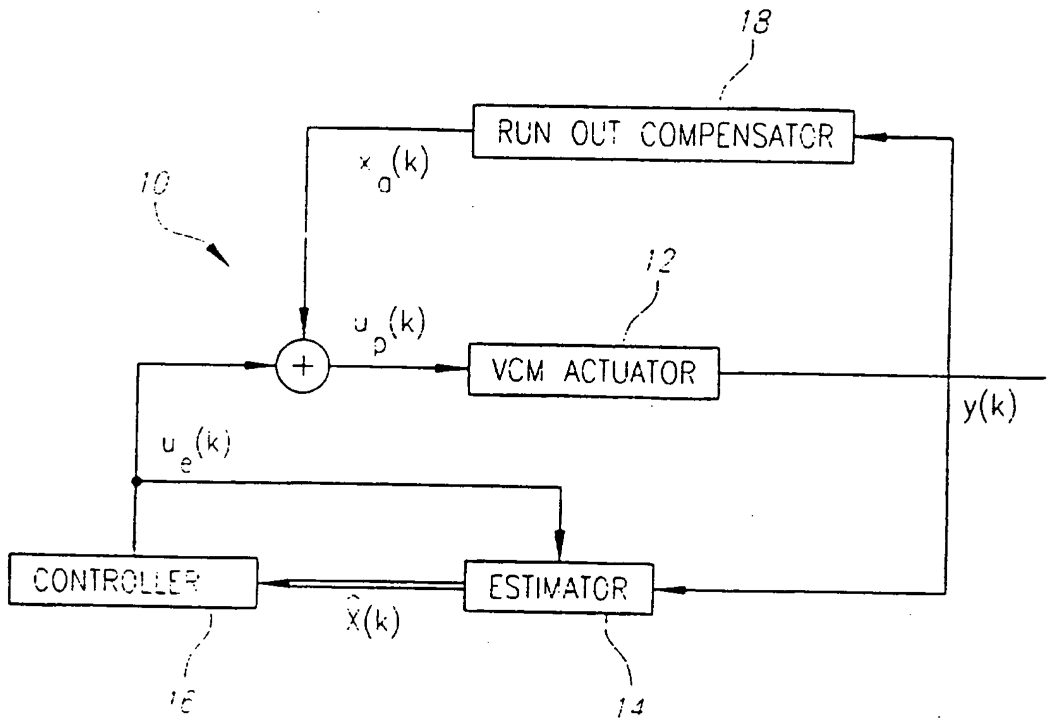

18
RUN OUT COMPENSATOR
$x_a(k)$
10
12
$u_p(k)$
VCM ACTUATOR
y(k)
$u_e(k)$
CONTROLLER
ESTIMATOR
$\hat{x}(k)$
16
14

FIG. 1

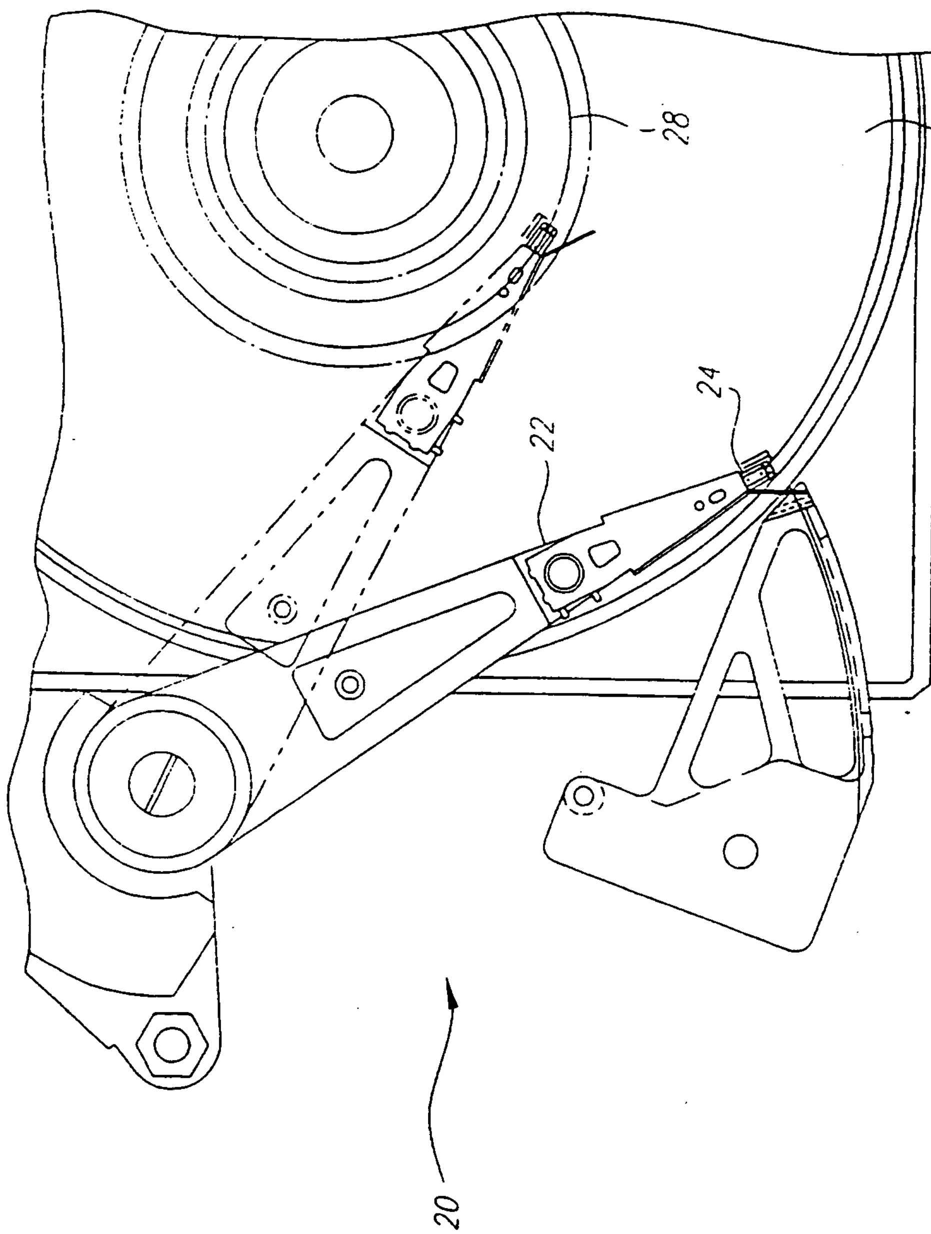


FIG. 2

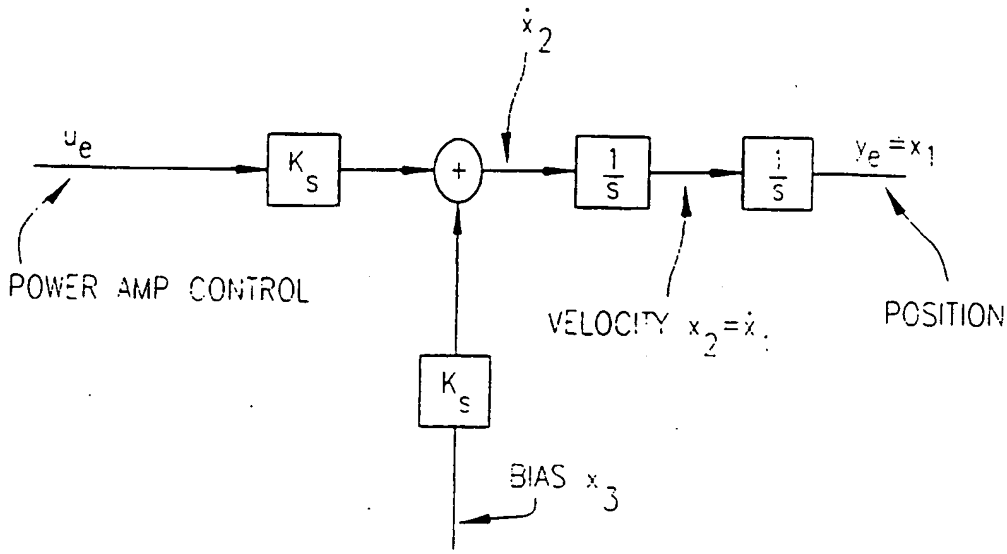

$\dot{x}_2$
u_e
K_s
+
$\frac{1}{s}$
$\frac{1}{s}$
$y_e = x_1$
POWER AMP CONTROL
VELOCITY $x_2 = \dot{x}_1$
POSITION
K_s
BIAS x_3

FIG. 3

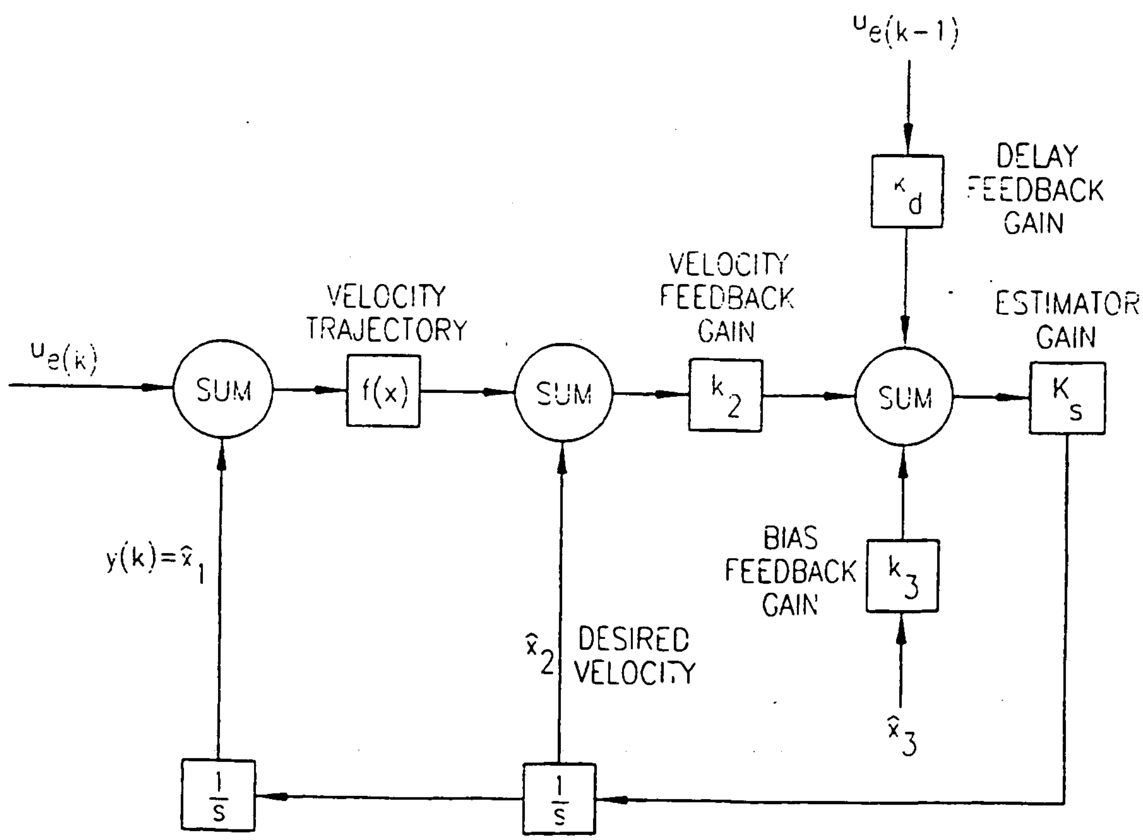

$u_{e(k-1)}$
K_d
DELAY FEEDBACK GAIN
VELOCITY TRAJECTORY
VELOCITY FEEDBACK GAIN
ESTIMATOR GAIN
$u_{e(k)}$
SUM
f(x)
SUM
k_2
SUM
K_s
$y(k)=\hat{x}_1$
BIAS FEEDBACK GAIN
k_3
$\hat{x}_2$ DESIRED VELOCITY
$\hat{x}_3$
$\frac{1}{s}$
$\frac{1}{s}$

FIG. 4

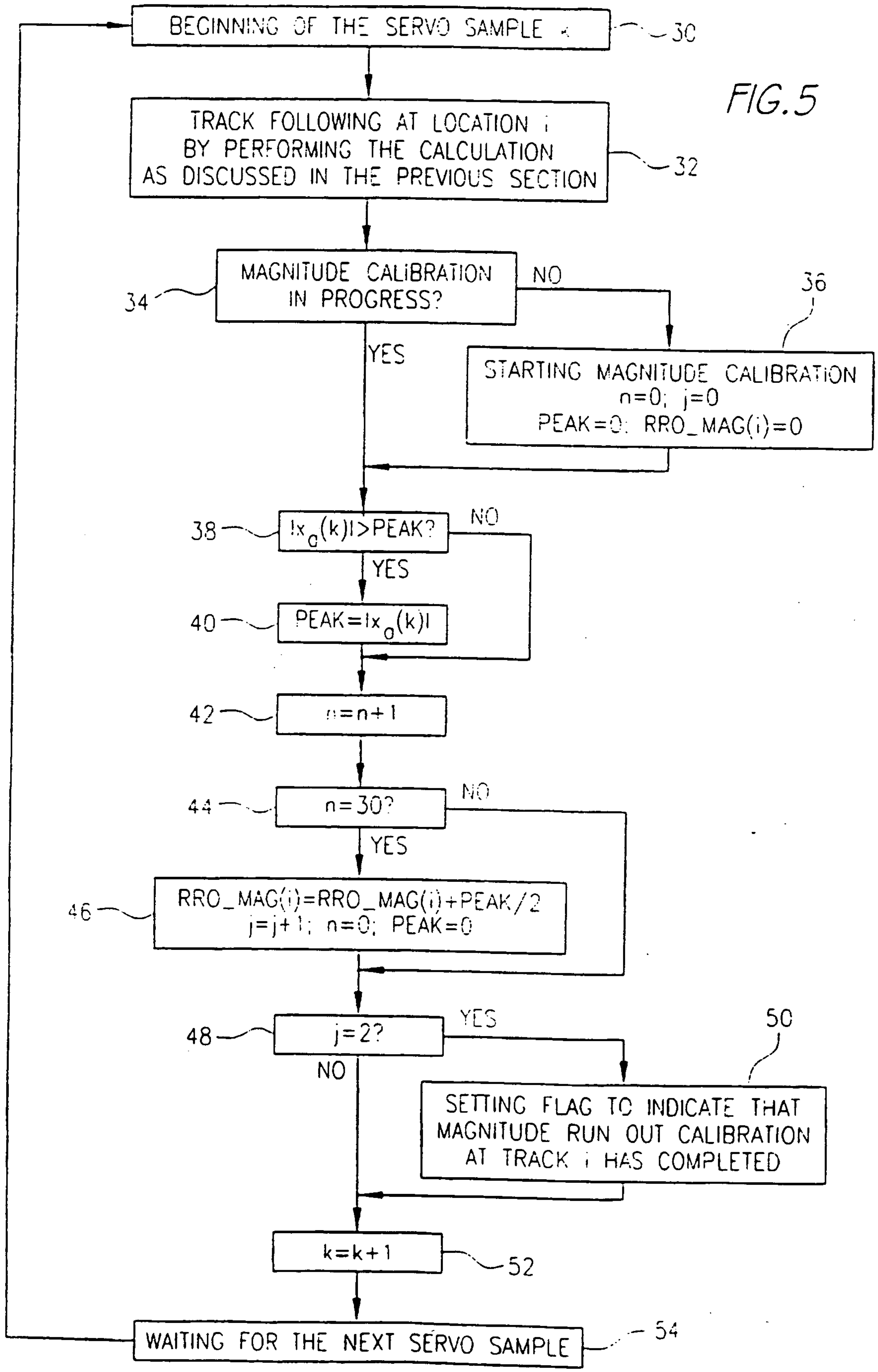

BEGINNING OF THE SERVO SAMPLE k
30
TRACK FOLLOWING AT LOCATION i BY PERFORMING THE CALCULATION AS DISCUSSED IN THE PREVIOUS SECTION
32
MAGNITUDE CALIBRATION IN PROGRESS?
34
NO
YES
36
STARTING MAGNITUDE CALIBRATION n=0; j=0 PEAK=0; RRO_MAG(i)=0
38
|x_a(k)|>PEAK?
NO
YES
40
PEAK=|x_a(k)|
42
n=n+1
44
n=30?
NO
YES
46
RRO_MAG(i)=RRO_MAG(i)+PEAK/2 j=j+1; n=0; PEAK=0
48
j=2?
YES
NO
50
SETTING FLAG TO INDICATE THAT MAGNITUDE RUN OUT CALIBRATION AT TRACK i HAS COMPLETED
k=k+1
52
WAITING FOR THE NEXT SERVO SAMPLE
54

FIG.5

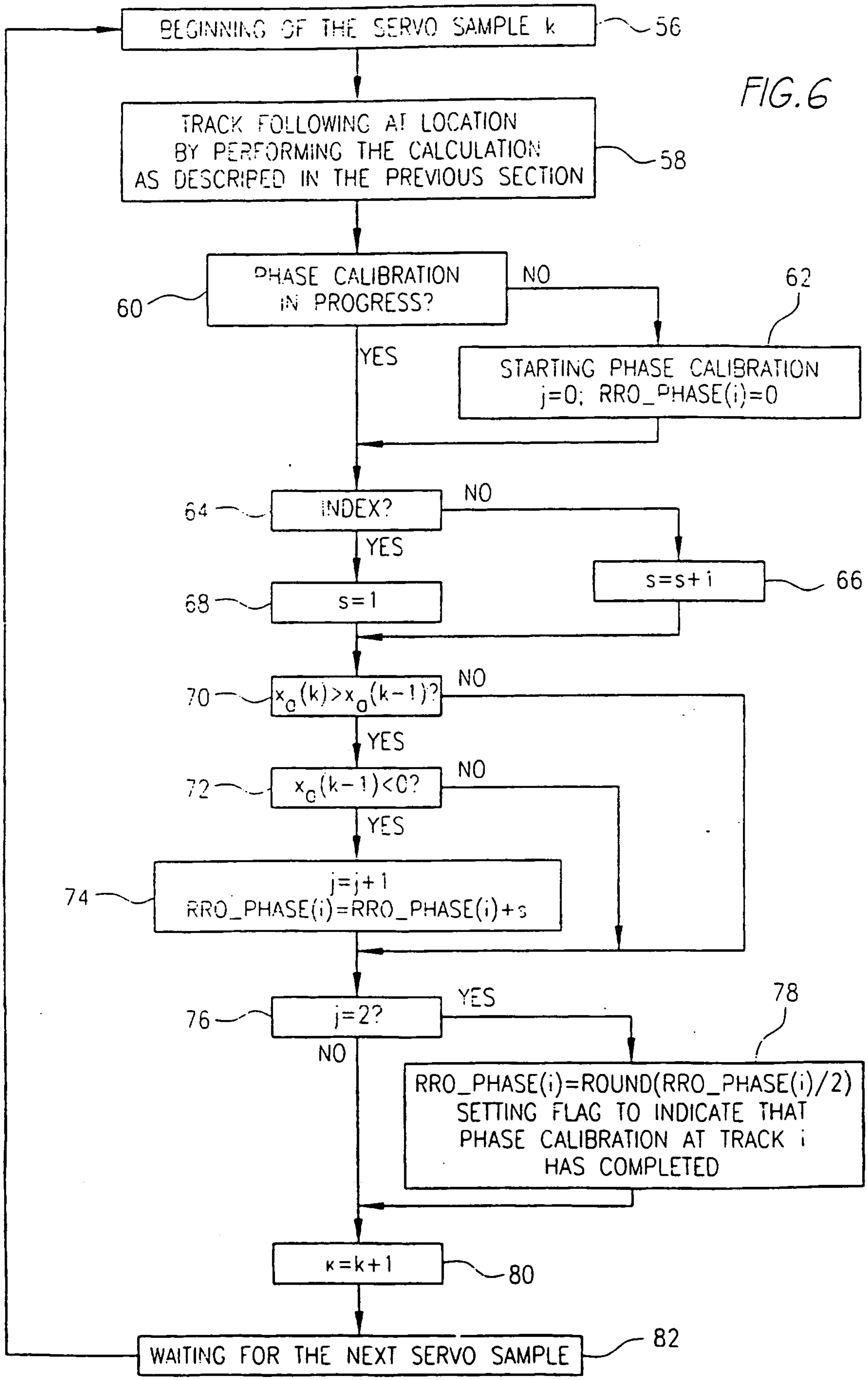

BEGINNING OF THE SERVO SAMPLE k
56
TRACK FOLLOWING AT LOCATION BY PERFORMING THE CALCULATION AS DESCRIBED IN THE PREVIOUS SECTION
58
PHASE CALIBRATION IN PROGRESS?
60
NO
YES
62
STARTING PHASE CALIBRATION j=0; RRO_PHASE(i)=0
INDEX?
64
NO
YES
s=s+i
66
s=1
68
$x_o(k)>x_o(k-1)$?
70
NO
YES
$x_o(k-1)<0$?
72
NO
YES
j=j+1 RRO_PHASE(i)=RRO_PHASE(i)+s
74
j=2?
76
YES
NO
78
RRO_PHASE(i)=ROUND(RRO_PHASE(i)/2) SETTING FLAG TO INDICATE THAT PHASE CALIBRATION AT TRACK i HAS COMPLETED
κ=k+1
80
WAITING FOR THE NEXT SERVO SAMPLE
82

FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/08638

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G11B 5/596
US CL :360/78.14, 77.07, 77.04
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 360/78.14, 77.07, 77.04, 78.04, 77.08, 77.02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, JPOABS, EPOABS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X/Y	US 5,444,583 A (EHRLICH ET AL.) 22 August 1995 (22/08/95), see entire document, especially, fig. 5, col. 10, line 56 through col. 16, line 7; col. 20, line 65 through col. 22, line 45/col. 11, line 56 through col. 13, line 2.	1, 2, 4 and 15/ 3, 5, 6, 9, 10 and 14
Y	US 5,402,280 A (SUPINO) 28 March 1995 (28/03/95), cols. 1-5.	3, 5, 6, 9, and 10
X/Y, P	US 5,585,976 A (PHAM) 17 December 1996 (17/12/96), see entire document, especially cols. 1 and 2, col. 8, line 40 through col. 11, line 38.	1, 2, 4 and 15/3, 5, 6, 9 and 10.

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 AUGUST 1997	24 SEP 1997

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	LARRY CULLEN
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0956

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/08638

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X/Y, P	US 5,550,685 A (DROUIN) 27 August 1996 (27/08/96), see entire document, especially figs. 1-4; col. 8, line 14 through col. 11, line 56.	1, 2, 5, 6, 10, 12 and 15/3, 4, 7, 9, and 14.
T	US 5,404,253 A (PAINTER) 04 April 1995 (04/04/95), see entire document.	1-15
T, P	US 5,617,388 A (ISHIOKA ET AL) 01 April 1997 (01/04/97), see entire document.	1-15.

THIS PAGE BLANK (USPTO)